# An improved analysis of $\mathbf{k}_\perp$ effects for SSA in hadronic collisions*

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The role of intrinsic transverse momentum both in unpolarized and polarized processes is discussed. We consider inclusive cross sections for pion production in hadronic collisions and for Drell-Yan processes. We reanalyze transverse single spin asymmetries (SSA) in inclusive pion production, $p^\uparrow p \to \pi X$, in terms of Sivers effect and show its contribution to $A_{UL}$ in semi-inclusive DIS (SIDIS).

In the last years a lot of experimental and theoretical activity has been devoted to the study of transverse single spin asymmetries (SSA) in hadronic collisions and in semi-inclusive DIS. In fact, perturbative QCD (pQCD) with ordinary collinear partonic kinematics leads to negligible values for these asymmetries. On the other hand several experimental results seem to contradict this expectation: *i*) the large polarization of Λ's (and other hyperons) produced in $p\,N \to \Lambda^\uparrow X$; *ii*) the large asymmetry observed in $p^\uparrow p \to \pi X$ and $\bar{p}^\uparrow p \to \pi X$; *iii*) the similar azimuthal asymmetry observed in $\ell\, p^\uparrow \to \ell\, \pi X$.

A possible way out from this situation comes from extending the collinear pQCD formalism with the inclusion of spin and partonic intrinsic transverse momentum, $\mathbf{k}_\perp$, effects. This leads to the introduction of new spin and $\mathbf{k}_\perp$ dependent partonic distribution (PDF) and fragmentation (FF) functions [1].

The role of $\mathbf{k}_\perp$ effects in inclusive hadronic reactions has been extensively studied also in the calculation of unpolarized cross sections, where it has been shown that, particularly at moderate $p_T$, these effects can be relevant [2].

Based on these considerations, in this contribution we present preliminary results both for polarized and unpolarized cross sections (and SSA) for inclusive particle production in hadronic collisions and SIDIS, using LO pQCD with the inclusion of intrinsic transverse momentum effects. Our main goal is to show

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that in our LO approach unpolarized cross sections can be reproduced up to an overall factor of 2-3, compatible with NLO corrections and scale dependences, which reasonably cancel out in SSA.

In this approach the unpolarized cross section for the inclusive process $A\,B \to C\,X$ reads

$$\begin{aligned} d\sigma \quad \propto \quad & \sum_{a,b,c,d} \hat{f}_{a/A}(x_a, \mathbf{k}_{\perp\, a}) \otimes \hat{f}_{b/B}(x_b, \mathbf{k}_{\perp\, b}) \\ & \otimes d\hat{\sigma}^{ab\to cd}(x_a, x_b, \mathbf{k}_{\perp\, a}, \mathbf{k}_{\perp\, b}) \otimes \hat{D}_{C/c}(z, \mathbf{k}_{\perp\, C})\,, \end{aligned} \tag{1}$$

with obvious notations. A similar expression holds for the numerator of a transverse SSA ($\propto d\,\Delta^N\sigma/d\sigma$), substituting, for the polarized particle involved, the corresponding unpolarized PDF (or FF) with the appropriate polarized one, $\Delta^N f$ (or $\Delta^N D$).

Let us start considering the role played by the intrinsic $\mathbf{k}_\perp$ in the unpolarized cross sections. The PDF and FF in Eq. (1) are given in a simple factorized form, and the $\mathbf{k}_\perp$ dependent part is usually taken to have a Gaussian shape:

$$\hat{f}_{a/A}(x, \mathbf{k}_{\perp a}) = f_{a/A}(x)\,\frac{\beta^2}{\pi}\,e^{-\beta^2\,k_{\perp a}^{\,2}}\;;\;\hat{D}_q^h(z, \mathbf{k}_{\perp h}) = D_q^h(z)\,\frac{\beta'^2}{\pi}\,e^{-\beta'^2\,k_{\perp h}^{\,2}}\,, \tag{2}$$

where the parameter $\beta$ ($\beta'$) is related to the average partonic (hadronic) $k_\perp$.

Analyzing a large sample of available data for several hadronic processes and in different kinematical situations, we find that an overall acceptable account of the corresponding unpolarized cross sections is possible by choosing, depending on the kinematical situation considered, $\beta = 1.0 - 1.25$ (GeV$/c)^{-1}$ (that is, $\langle\, k_\perp^2\,\rangle^{1/2} = 0.8 - 1.0$ GeV$/c$).

For the process $p\,p \to \pi\,X$, some experimental results for SSA are also available, and we can see how our approach works for SSA and unpolarized cross sections at the same time. In this case we can have $\mathbf{k}_\perp$ effects in the fragmentation process also. A direct $z$ dependence of the $\beta'$ parameter in Eq. (2) seems to be favored, $1/\beta'(z) = \langle\, k_{\perp\pi}^{\,2}(z)\,\rangle^{1/2} = 1.4\,z^{1.3}\,(1-z)^{0.2}$ GeV$/c$.

Let us now consider the SSA in $p^\uparrow\,p \to \pi\,X$, within the same approach and assuming it is generated by the Sivers effect [3] alone, that is from a spin and $\mathbf{k}_\perp$ effect in the PDF inside the initial polarized proton, described by the Sivers function $\Delta^N f_{q/p^\uparrow}(x, \mathbf{k}_\perp)$. Other possible sources for SSA, like the so-called Collins effect [4], concerning the fragmentation of a polarized parton

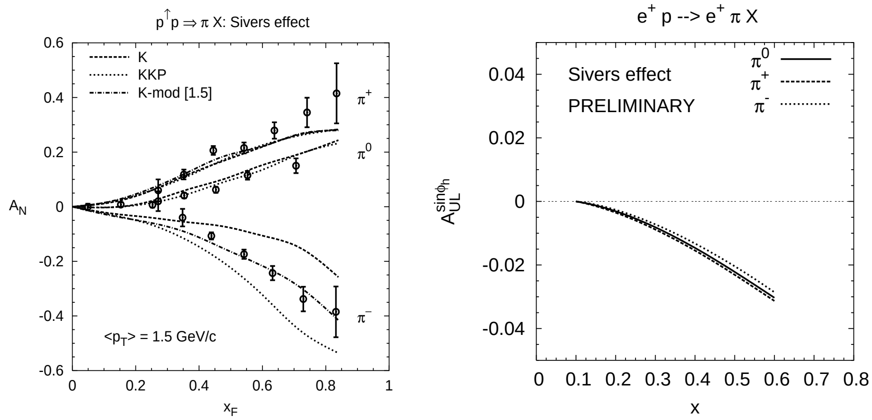


Figure 1: SSA in (a) $p^\uparrow\, p \to \pi\, X$ vs. $x_{_F}$ and (b) $\ell\, p^\uparrow \to \ell' \pi\, X$ vs. $x$; see plots and text for more details.

into the final observed pion, are not considered here. Analogous studies have already been performed [5]; here we show the first results with full treatment of $\mathbf{k}_\perp$ effects and partonic kinematics. These results are in good qualitative agreement with previous work.

The numerator of the SSA, $d\sigma^\uparrow - d\sigma^\downarrow$ can be expressed in the form of Eq. (1), with the substitution $\hat{f}_{a/A}(x, \mathbf{k}_\perp) \to \Delta^N f_{q/p^\uparrow}(x, \mathbf{k}_\perp)$. For the Sivers function we choose an expression similar to that of the unpolarized distribution:

$$\Delta^N f_{q/p^\uparrow}(x, \mathbf{k}_\perp) \propto \Delta^N f_{q/p^\uparrow}(x)\, k_\perp\, \exp\left[-\beta^2 k_\perp^2/r\right]\, \sin\phi_{k_\perp}\,, \tag{3}$$

where $\phi_{k_\perp}$ is the angle between $\mathbf{k}_\perp$ and the polarization vector of the proton. By comparison with data we can fix both $r$ and $\Delta^N f_{q/p^\uparrow}(x)$.

In Fig. 1a we show our preliminary estimates of $A_N$ with Sivers effect at $E$ = 200 GeV and $p_{_T}$= 1.5 GeV/c, vs. $x_{_F}$, for three different choices of the pion FF: K [6], KKP [7] and a modified version of K. Data are from [8]. The SSA for $\pi^+$ and $\pi^0$ is well reproduced independently of the FF set. Interestingly, the $\pi^-$ case shows a stronger sensitivity to the relation between the leading and non-leading contributions to the fragmentation process, which cannot be extracted from present experimental information.

A more direct way to extract the Sivers asymmetry is the analysis of SSA in

Drell-Yan processes, that is the production of $\ell^+\ell^-$ pairs in the collision of two hadrons $A$ and $B$ [9]. By considering differential cross sections in the squared invariant mass ($M^2 = (p_a + p_b)^2$), rapidity ($y$) and transverse momentum of the lepton pair ($\mathbf{q}_{_T}$) and integrating out the di-lepton angular dependence, the SSA reads ($q_{_T}^2 \ll M^2 \ll M_Z^2$ and $k_{\perp a,b}^2 \simeq q_{_T}^2$)

$$A_N = \frac{\sum_q e_q^2 \int d^2\mathbf{k}_{\perp q}\, \Delta^N f_{q/A^\uparrow}(x_q, \mathbf{k}_{\perp q})\, \hat{f}_{\bar{q}/B}(x_{\bar{q}}, \mathbf{q}_{_T} - \mathbf{k}_{\perp q})}{2\sum_q e_q^2 \int d^2\mathbf{k}_{\perp q}\, \hat{f}_{q/A}(x_q, \mathbf{k}_{\perp q})\, \hat{f}_{\bar{q}/B}(x_{\bar{q}}, \mathbf{q}_{_T} - \mathbf{k}_{\perp q})}\,. \tag{4}$$

Notice that other sources of SSA would lead to a contribution to $A_N$ that vanishes upon integration over all final angular configurations of the $\ell^+\ell^-$ pair.

One further uncertainty concerns the sign of the asymmetry: as noticed by Collins and Brodsky [10], the Sivers asymmetry has opposite signs in Drell-Yan and SIDIS, respectively related to $s$-channel and $t$-channel elementary reactions. As in $p\,p \to \pi X$ we expect that large $x_{_F}$ regions are dominated by $t$-channel quark processes, we tentatively assume that the Sivers function extracted from $p-p$ data should be opposite to that contributing to D-Y processes.

Finally we consider the Sivers contribution to the azimuthal asymmetry in SIDIS. In this case the numerator of the transverse SSA reads

$$d\Delta\sigma = |\mathbf{S}_{_\perp}| \sum_q e_q^2\, \Delta^N f_{q/p^\uparrow}(x_q, \mathbf{k}_{_\perp}) \otimes \frac{d\hat{\sigma}^{\ell q \to \ell q'}}{d\hat{t}} \otimes D_{\pi/q}(z_q, \mathbf{k}'_{_\perp})\,, \tag{5}$$

where $\mathbf{S}_\perp$ is the transverse component of the target spin in the $\gamma^* - p$ cm frame. In particular for longitudinal polarization ($\mathbf{S}_L$) in the LAB frame

$$|\mathbf{S}_{_\perp}| = |\mathbf{S}_L|\, \sin\theta_\gamma \simeq |\mathbf{S}_L|\, 2\,(m_p/Q)\, x\sqrt{1-y}\,. \tag{6}$$

From Eq. (6) we see that the contribution in Eq. (5) is globally higher twist.* In Fig 1.b we give our estimate of the $(\sin\phi)$-weighted asymmetry $A_{UL}$, for HERMES kinematics from Eq. (5). It is important to remark (see also [11]) the tiny value of $A_{UL}$, its negative sign and the $u$ flavor dominance also for $\pi^-$; this last feature is due to the relatively small difference between favored and unfavored FF's in the $z$ range covered at HERMES.

*Other possible contributions of the same twist are not considered here.

In conclusion, we have presented here preliminary results of a consistent study of partonic transverse momentum effects both in unpolarized and polarized cross sections (and SSA) for inclusive particle production in hadronic collisions.

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